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COMMENTARY

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Key Points:
- Recent literature on self-aggregation of convective cloud fields is surveyed
- Process holism in idealized settings is edifying, albeit with limited relevance
- Process synthesis is the work's greatest strength, and could be extended

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Gregarious convection and radiative feedbacks in idealized worlds

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Abstract What role does convection play in cloud feedbacks? What role does convective aggregation play in climate? A flurry of recent studies explores "self-aggregation" of moist convection in diverse simulations using explicit convection and interactive radiation. The implications involve upper level dry areas acting as infrared windows—the climate system's "radiator fins." A positive feedback maintains these: dry columns undergo radiative cooling which drives descent and further drying. If the resulting clumpiness of vapor and cloud fields depends systematically on global temperature, then convective organization could be a climate system feedback. How reconcilable and how relevant are these interesting but idealized studies?

1. Introduction

Three recent JAMES papers motivate this essay [*Arnold and Randall*, 2015, hereinafter AR15; *Bretherton and Khairoutdinov*, 2015, hereinafter BK15; *Holloway and Woolnough*, 2016, hereinafter HW16], and Figure 1 asks its question graphically: What can idealized simulations teach us about patchy convection on Earth? After background for a general readership on the physics of the problem, compromises used in simulations, and methods of diagnosis, broader lessons and prospects are surveyed.

2. Temperature, Water Vapor, and the Clumpiness of Moist Convection

Gravity destabilizes radiatively cooled air above a sun-heated surface, making it overturn or "convect." Convection keeps temperature profiles in a statistical or "quasi-" equilibrium state that is as close to convective neutrality as Earth's gravity is strong. But latent heat release in cloudy updrafts means that moist convective "neutrality" is actually a stable thermal stratification (called a *moist adiabat*). In such a stratified fluid, gravity is also efficient at flattening density surfaces by internal wave dispersion, especially in the weakly rotating tropics. The result of all this is that gravity's strength maintains the tropical troposphere in a state of Quasi-Equilibrium with Weak Temperature Gradients (QEWTG), although the causal reason varies from convective QE [*Arakawa and Schubert*, 1974] on large scales to WTG [*Sobel and Bretherton*, 2000] on local scales.

Given the efficiency of internal wave heat transport, the net condensation heating associated with precipitation can do its climatic job of balancing widespread infrared cooling from narrow, localized spots. Indeed, convection *prefers* localization and small scales, in the Darwinian natural-selection sense [*Bjerknes*, 1938; *Lilly*, 1960]. Empirically, though, individual spotty updrafts tend to be organized into broader-scale clumps or patches of activity. These clumps are gatherings of both humidity and clouds, coupled to structures in wind and density fields. What processes govern their locations, sizes, and character? Ecosystems and civilizations and family picnics hang in the balance.

3. Target of Recent Works: Long-Lived Aggregation of Humid and Dry Areas

Aggregation of convection occurs for different reasons on different time and space scales [*Jeevanjee and Romps*, 2013]. Very locally, "triggering" of updrafts by adjacent downdraft outflows (cold pools) in the boundary layer overcomes the inhibition in a metastable system, making storms multicellular. Internal waves above the boundary layer, including those excited by prior convection [*Mapes*, 1993], shape the inhibition field itself on a broad spectrum scales. Moisture accumulations can occur in transient ways [*Craig and*

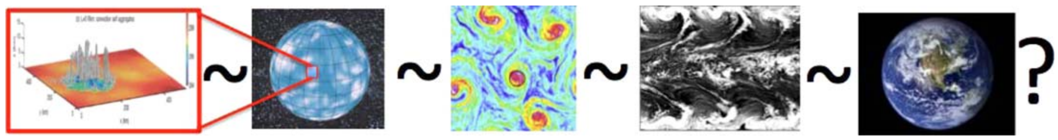

Figure 1. A visual question (left to right) asking if convective clumping in different idealized domains is similar in character (∼), to each other and to the real world. Images are from *Muller and Held*, 2012, AR15, *Khairoutdinov and Emanuel*, 2013, BK15, and NASA's Blue Marble.

Mack, 2013; *Muller and Bony*, 2015], but water vapor as a long-lived and radiatively active tracer also has more lasting effects.

These recent papers (AR15, BK15, HW16) all exhibit slow, tracer-mediated aggregation by "radiative-convective instability" [*Emanuel et al*., 2014; *Wing and Emanuel*, 2014, hereinafter WE14]. The instability involves infrared radiation acting on wind-sculpted humidity and cloudiness fields, with a secondary role for wind speed-dependent surface fluxes. But the winds are themselves shaped by the aggregation pattern, in an evolutionary process as relentless as it is slow (days to weeks, the time scale of tropospheric vertical turnover or water vapor residence time). Even in the absence of structured boundary conditions (continents and oceans) to organize the outcome, self-aggregation drives simulated atmospheres toward a bimodal patchwork of humid and dry areas. The connection to climate is that dry areas act as planetary "radiator fins" (*Pierrehumbert*, 1995).

This problem encompasses the whole suite of atmospheric climate processes: fluid dynamics, thermodynamics, and all three hard nuts of atmospheric physics (turbulent fluxes, condensed water physics, and radiative energy transfer). This rich holism of processes allows even highly idealized configurations to dare shed light on the climate-relevant WCRP Grand Challenge [*Bony et al*., 2015] questions posed in the Abstract.

In these papers, aggregation also provides a useful playground for exploring routes to diagnosis and understanding. Atmospheric science knows its governing equations already; absolutely so, in the case of simulations. What makes prediction hard are scale interactions, which form an unnervingly lacy-looking foundation for strongly desired inferences about the largest and longest scales. Consider the terminology of a time domain differential equation with multiple terms (*tendencies*) on its right-hand side ($\partial q/\partial t = A + B + C + \ldots$). How can the causality of small "climate" changes (low-frequency variations which, by definition, flow from the small-magnitude net tendency) be meaningfully diagnosed amidst all the much larger tendencies driving large-amplitude and rapidly varying "weather"?

One mathematical tool for seeing beyond, the distractions of weather is the exact vanishing of any horizontal flux divergence when integrated over Earth's whole surface. In the time domain, the trick is similar: seek a quantity unaffected by weather. These studies use an almost-conserved scalar, vertically integrated moist static energy (VIMSE). Since water phase changes make compensating contributions to temperature and humidity terms, their sum vanishes in constructing MSE. Furthermore, vertical flux divergences within the atmosphere (describing the complicated processes of radiation, precipitation, and turbulence) vanish in the vertical integral, leaving only boundary values: top-of-atmosphere radiation and surface heat and moisture fluxes.

Besides the parsimony of its budget equation, VIMSE has the further virtue (thanks to WTG again) of being almost equivalent to column humidity measures such as "precipitable water," PW, a very strong predictor of deep moist convection [*Bretherton et al*., 2004; *Neelin et al*., 2009]. These papers freely interchange VIMSE and column humidity as both budget objects and abstract coordinates for diagrams. Thunderstorms, with all their complications, are invisible through VIMSE goggles: while this is little help for picnic planning, long-lasting radiatively maintained structures (climate writ small) can be diagnosed without distraction, and sensitivities to modeling choices can be explored.

4. Affording the Simulations: Compromises

With the governing equations for moist dynamics and software codes to solve them, atmospheric science can now afford three of the four virtues of simulation: process complexity, at high resolution, on large domains, for a long time. These three papers interestingly span the range of compromises:

1. HW16 used a modest-sized (576 km), homogeneous, spatially cyclic domain with fairly coarse "cloud-permitting" resolution (4 km mesh). Many experiments could be performed, so this paper is notable for its thoughtful process experimentation, aimed at reconciling various questions from the pioneering studies in this area. Although HW16 retained a complicated subgrid convection parameterization, its action was attenuated so that most of the key processes occurred explicitly at grid scales.
2. BK15 used an equally coarse 4 km mesh (but without such parameterizations) on an almost planetary-sized domain. As a result, only 2 months of simulation time could be afforded. This study is notable for having a global circulation, driven by an Earth-like latitudinal surface temperature gradient. It also features disgnostic decompositions of its large domain into octaves of scale in the east-west direction, with implications for predictability limits arising from convective chaos.
3. AR15 also simulated an Earth-sized atmosphere, but with a coarse grid (T42 or about 2.8° lat-lon cells) and "superparameterized" convection. Superparameterization involves integrating a small-domain (32 columns in a cyclic line) cloud-permitting (4 km spacing again) model within each global grid cell, coupling only its domain-averaged profile with the global flow solver. Spatial scales of motion around 10^2–10^3 km are notch filtered out of such a model: they exist neither on the globe nor within the cloud model. Since mesoscales impose great computational costs on atmosphere models, as well as inconvenient unrepresentativeness on point observations, a world devoid of such scales is our forebears' daydream come true [*Fleming*, 2007], a fascinating reference case.

5. Enablers of Interpretation: Concepts, Diagrams, and Approximations

A major driver of this flowering of literature is a space in which the diverse simulations can be compared: clever, informative diagrams that fit on a 2-D static page. Three key tactics are: (1) use of a master scalar to encode horizontal space, (2) use of a second-moment (variance) budget, and (3) a way to unpack the physically important vertical structure.

1. A master scalar can be used to collapse or encode horizontal space—whether 2-D or 3-D, large or small—into a single statistical dimension. These works all use VIMSE (or its near-equivalent, column humidity) or the corresponding rank variable (Figure 4 of WE14; Figure 5 and others in AR15, Figures 9a and 9c of BK15). Figure 5 versus Figure 6 of HW16 nicely compare the rank versus raw depictions.
2. Budgets of the *spatial variance* of VIMSE inside the domain allow a clever visualization of how various physical tendencies contribute to a simulation's overall propensity to aggregate. Budget terms are covariances, lucidly expressed with zero-centered diverging color scales (like Figure 4 of WE14). Analyses of variance and covariance always invite orthogonal decompositions, for example, by Fourier wavelength octaves (factors of 2) as in Figure 10 of BK15.
3. While VIMSE is useful, the vertical dimension remains too physically important and heterogeneous to merely be integrated over. Besides top-of-atmosphere radiation and surface fluxes for each air column, VIMSE budgets have a horizontal transport term that depends critically and interestingly on the vertical *profile* of airflow. "Horizontal transport" is taken here to mean the *convergence of horizontal flux*. Counterintuitively, this is often dominated by *vertical advection*—for instance, in the horizontal transport of heat by internal waves that maintains WTG. Convergence of horizontal flux is equal to 3-D advection, using mass continuity. Bottom-heavy or "shallow" circulations are especially effective at transporting moisture (since it is concentrated at low altitudes, where temperatures are warm) and thus VIMSE. The clumpiness feedback described in the abstract, for example, is an upgradient transport driven by bottom-heavy radiative cooling.

To understand more, transport needs to be subdivided into parts, such as "diffusive" transport by "small" scales versus "advective" transport by large-scale or resolved flows. The latter can be further subdivided into a vertical overturning circulation (which performs vertical as well as horizontal advection) versus purely horizontal advection by nondivergent components of the horizontal wind field. The latter is a very large term in Earthly flows, so its neglect or distortion is a profound shortcoming of cyclic limited-area simulations. The overturning flow can be depicted on the page by an elegant streamfunction, even in VIMSE-encoded horizontal space (*Bretherton et al*. [2005, Figure 10], which spawns Figure 7 of AR15, Figure 9 of BK15, and HW16 Figures 7, 8, 11, and 15). HW16 further extends this approach by indicating *hypothetical* overturning streamfunctions, such as that ascribable to radiation acting in isolation. Although a streamfunction gives an incomplete indication of total VIMSE transport, it is at least a useful reference pattern to overlay on other colorized field depictions to delineate ascending versus descending airflow regimes.

A deeper root also underlies this progress: the lucid expression of thermodynamics as Moist Static Energy (MSE), instead of entropy (whose formulas bristle with logarithms) or potential temperatures (whose formulas bristle with exponentials) [for a crisp exposition see *Betts*, 1974]. The simple sum of sensible, potential, and latent contributions to total energy is enormously clarifying, yet is sufficiently rigorous and conservative that a popular numerical cloud model can be based on it (*Khairoutdinov and Randall*'s [2003] SAM model, used in both BK15 and AR15). In MSE, it is obvious at an algebraic level, and not merely as a computed result, that VIMSE patterns in the WTG approximation are equivalent to patterns of column-integrated water vapor.

6. Lessons and Prospects

This synthetic literature is at a minimum very educational—all the more so for its idealization. Its process set outlines a core graduate education in a field arguably at risk of overspecialization (a conclusion also highlighted in *Emanuel*'s [2015] AGU Bjerknes lecture on this subject). A few refinements could further enrich that aspect. For instance, scale interactions are glossed over in the encoded-space diagnostics, so BK15's overt scale decompositions are a welcome addition. Since larger-scale disturbances have greater wind per unit horizontal divergence, a wind speed or surface flux display might also be used to embody the scale spectrum in relevant terms. More broadly, the overturning stream function for all its elegance is only a very partial gesture at transports of MSE and condensate, which might as well be shown in full. The process of radiative energy transfer could also be illuminated better. For instance, the mapping of spectral bands in water vapor's spectroscopy onto the vertical structure of the vapor-subsidence feedback awaits elucidation, and even has relevance, at least to the extent that dry skies are free of the profound untidiness of clouds.

Are there outright discrepancies for additional idealized studies to resolve? While the various studies highlight different processes driving aggregation or VIMSE variance growth, many of those differences are rooted in the idealizations: different domain sizes and symmetries [*Wing and Cronin*, 2015], at early versus late stages of development, in different models. The sensitivity of self-aggregation to mean temperature (the gateway to grand global climate feedback questions) is surely also configuration dependent. Coupling to an energy-conserving lower boundary to make a true climate system would undoubtedly expose the usual maddening model dependences of stable clouds. Still, explicit convection simulations can at least set targets for models with parameterized processes [*Tobin et al*., 2013; *Coppin and Bony*, 2015].

The time domain is where it becomes hardest to relate these idealized weeks-long aggregations from rest in closed-domain simulations to the reality of Earth's open, sheared air masses traversing the radically heterogeneous atmosphere, seeded by a prior eternity of multiscale weather. While AR15 suggest that the 50 day Madden-Julian Oscillation (MJO) might plausibly correspond to some of their idealized simulations, self-aggregation is not exactly a leading candidate for the real MJO's "onset" [e.g., *Yoneyama et al*., 2013]. Perhaps a closer look at very early stages of self-aggregation achieved on time scales relevant to Earthly air column lifetimes (days, not weeks) could begin to build a bridge to realism. Bimodality of water vapor appears within a day at upper levels and builds downward [*Mapes*, 2001; *Zhang et al*., 2003]. Evidently, the dry mode does not impede convection (and thus aggregate its horizontal area coverage) until it reaches middle or lower troposphere levels. Perhaps matching the observed altitude depth of bimodality could link evolutionary stages in the simulations to the time scales on which air columns are partly isolated in the real atmosphere's churn. Such an effort might encourage some needed clarity about which coarse-grain scales are being considered, and why.

In the sober currency of global climate feedbacks (dimensions: W m^{-2} K^{-1}), cloud field morphology changes are a tricky target of study. They have been posited as a negative feedback, an "adaptive infrared iris" [*Lindzen et al*., 2001]. Could such an effect be reliably detected if it were real? Such a feedback of climate change relevant magnitude was imposed in a coupled model [*Mauritsen and Stevens*, 2015], whose very subtle local differences could set a bar for observational detection through conditional sampling by methods like *Tobin et al*. [2012]. Given the delicacy of global energy imbalances, aggregation probably joins the long list of "potentially nonneglegible" effects. While this list forms a useful overarching justification for diverse Earth system science, one can wonder: will detail work on climate's subsystems ever be accurate enough to sum up reliably (in the $\partial T/\partial t = A + B + C + \ldots$ sense)? I suspect not unless there are interactions among the parts that conspire to act as a true "system" on a higher abstraction level, obeying higher-level principles or at least inspiring useful postulations thereof [e.g., *Lovelock*, 1972].

In short, the great strength of this burgeoning research area, besides being elegant and edifying, may be not as a literal path toward estimating one more nonnegligible feedback among many, but as a microcosm for developing new conceptual modes of thinking about emergent phenomena involving ever-larger sets of processes. In other words, these studies add a rung to the hierarchy of models that comprises understanding [*Held*, 2005]. Gaining confidence in full-complexity Earth System models, the lenses of our ultimate peering into the grand challenge of climate, seems impossible without idealized but synthetic work like this ascendant literature on aggregation.

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